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Lysimetric Measurements of Evapotranspiration Rates in the Eastern United States[1]

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ABSTRACT

A review is presented of various methods to determine the evapotranspiration rate under field conditions. It is shown that, at the present time, the data which have been collected by a suitable lysimetric method are the only ones that exist in quantity and that, at the same time, can be considered as reliable.

The conditions which must be met by a lysimeter installation for the accurate and representative measurement of the evapotranspiration rate are reviewed. It is shown that both the exposure as well as the moisture conditions in the soil of the lysimeter must be representative of those in the surrounding area if realistic values are to be obtained.

Selected data from four locations in the Eastern United States are presented and compared. It is shown that data for grass cover under a variety of geographic and climatological conditions do not vary greatly from one another. Such dependable comparisons as are available between different crops show that the differences between corn, wheat, and meadow crops are small though not insignificant. The need for additional and adequate lysimetric measurements of evapotranspiration rates in the eastern half of the United States is discussed as well as the necessity for making pertinent meteorological measurements to aid in the generalization of the data.

In this paper, the term "evapotranspiration" is meant to designate the process of movement of water from the earth's land surface to the atmosphere in vapor form. Thus, it includes evaporation from the surface of the soil and plant as well as transpiration of water by leaves and the net flow of water vapor across the liquid-air interface in the free pore space of the soil. Hydrologists commonly encompass all these terms under evaporation. Specifically excluded is any downward movement of water out of the root zone, although this term is sometimes erroneously included under evapotranspiration.

It is unnecessary at this point to elaborate upon the significance of a knowledge of evapotranspiration under field conditions. Methods to determine the evapotranspiration rate may be divided into three categories, as follows:

1. Measurement of the changes in moisture content of the natural soil profile.
2. Measurement of the changes in moisture content of a confined, disturbed or undisturbed soil sample.
3. Measurement of the vapor flux through the lower atmosphere (either energy balance or mass transport method).

Method *(1)* is historically the oldest one and is still widely used. By varying means, the moisture content of the soil throughout the profile is measured from time to time and moisture losses are determined. It is generally accepted that this method is precise only for periods of several days because of sampling and instrumental errors in the moisture determination.

Less commonly understood is the difficulty of separating downward flux from flux into the atmosphere. Since moisture does not, of necessity, flow with the moisture gradient and since absence of variation in moisture content is not synonymous with zero flow, the interpretation of moisture content data is difficult. Only in dry climates with infrequent rainfall or irrigation are the difficulties less. In the Eastern United States, where rainfall is frequent and soils often shallow, the moisture profile method must be ruled out as an accurate means for finding evapotranspiration rates.

The third, or micrometeorological category of methods for finding the vapor flux holds the most promise for future widespread and frequent measurements of evapotranspiration rates. At this moment, however, there are many instrumental and theoretical difficulties to overcome and the amount of reliable data is too small for discussion.

Accordingly, there remains the study of moisture changes in a body of soil confined in lysimeters as the only practicable method for measurement of evapotranspiration rates with adequate precision. The confinement of the soil body has the obvious purpose of preventing lateral moisture exchange and catching any and all percolate for precise measurement. Nonetheless, lysimeters can also easily yield erroneous values for the evapotranspiration rate unless the construction and operation meets certain requirements.

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Required Lysimeter Practice

By the nature of its construction, a lysimeter prevents the natural vertical flow and distribution of water. This is illustrated in figure 1, which refers only to the initial condition after rain or irrigation. At that time a zero-pressure plane is present at the bottom and thereby the moisture tension as well as moisture content are different from those in the surrounding soil. This may have two effects: first, more water may be available for evapotranspiration during a prolonged dry spell, and, second, the development of the root system of crops grown in the lysimeter may differ from that in the surrounding area.

In so-called constant water table lysimeters, the same applies except that then the water table is the zero-pressure plane. Only when information is sought about the evapotranspiration rate under conditions of a permanent and high water table will a constant water table lysimeter duplicate outside conditions.

The difficulty may be reduced by making the lysimeters deep, so that they extend well below the root zone as was done, for example, in the Coshocton lysimeters (5). Obviously, it is more difficult to construct a deep lysimeter. A more basic solution is to maintain tension at the bottom of a lysimeter deep enough to allow normal root development. This requires a rigid porous support for which the bubbling pressure is higher than the highest tension one wishes to establish. Tension can then be maintained to equal or approximate the tension in the surrounding profile at the same depth. This principle has been recognized for some time but it is not yet widely understood or applied. An example of its application is the Davis, California weighing lysimeter.

When lysimeters are employed to measure actual evapotranspiration rates, including periods of drought, it seems essential that they are either quite deep or fitted with a tensioning device at the bottom. On the other hand, when the objective is to determine the maximum evapotranspiration rate, the moisture conditions in the soil column are not critical as long as root growth is normal. This still rules out very shallow or high water table lysimeters.

Ideally, lysimeters should contain an undisturbed, representative profile. This again is important when actual evapotranspiration is under study. In a disturbed profile, moisture transmission, moisture retention, and root distribution is likely to be different from that of the original profile and measurements may not be representative. When maximum evapotranspiration is studied, the physical constitution of the soil is of less significance.

Another important aspect of lysimeter practice is the maintenance of uniform conditions around the lysimeter. The lysimeter is only then a true sample of prevailing field conditions if its physical environment is identical to that typical for the field. This means that a lysimeter should be surrounded by an appreciable area planted, fertilized, watered, and managed in the same manner as the lysimeter. This point, formerly much neglected, is now gradually being recognized. It has been elaborated. among others, by Mather (9).

Also, the rim or border of the lysimeter should be as small as possible and heat flux and soil temperatures in the lysimeter should equal values typical for the surrounding field.

Finally, we must consider the manner in which the lysimeter is operated in order to obtain the necessary data. The simplest way is to measure percolate only. This may be done accurately with a minimum of expense. The difficulty is that percolate is only available after rains or irrigation and equilibrium is established slowly. In the meantime, the amount of water stored in the soil may have changed appreciably so that the value of (rain — percolate) is not necessarily equal to evapotranspiration for the period at hand.

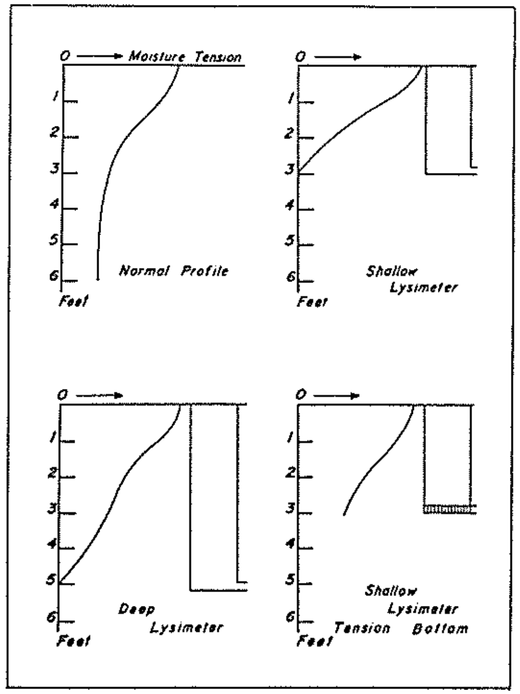

Figure 1—Idealized soil moisture tension vs. depth relations after rain or irrigation. Top left: A normal field profile; top right: A shallow lysimeter with bottom drainage; bottom left: A deep lysimeter with bottom drainage; bottom right: A lysimeter with tension plate at bottom for drainage.

Therefore, natural, nonirrigated lysimeters yield dependable values for the evapotranspiration rate only over long periods between major rains. Seasonal and annual values are obtained with considerable precision. A good example are the nonweighing lysimeters at Coshocton.

If values of maximum evapotranspiration rates are to be measured the lysimeters should be irrigated frequently, for example, every 4 or 5 days, unless rainfall intervenes. In this manner, values may be obtained for the evapotranspiration rate over periods of corresponding lengths. By judicious choice of the amount of irrigation water the error due to differing storage can be minimized as shown by Gilbert (2) and Green (3).

Similar considerations apply to constant water table lysimeters. When used to measure actual water loss the movement of water from the water table into the root zone may not always be rapid enough to equal the evapotranspiration rate. Rain in sufficient quantity is needed to restore the original condition. Even though constant water table lysimeters may be read daily, they cannot be considered as supplying accurate daily evapotranspiration rates.

The use of constant water table lysimeters for measuring the maximum evapotranspiration rate is questionable for the same reason as given before. Unless the water table is very close to the surface, the values obtained may be too low. Much depends on the nature of the crop and soil in question and many installations will probably give adequate data.

In order to obtain accurate values of the evapotranspiration rate over periods of a day or less, down to 5- and 10-minute periods, lysimeters must be weighed. The weight must be determined with considerable sensitivity because of the dead weight of the soil and container, but weighing techniques are adaptable to the problem. Weighing lysimeters are costly but in the absence of a substitute method, several such installations have been constructed.

In summary, lysimeters are now the most dependable means to measure the evapotranspiration rate directly, but the installation must meet several requirements for the data to be representative of field conditions. These are, in the main:

1. Representative exposure of the lysimeter.
2. Representative moisture content, moisture tension, thermal conditions and root distribution in the lysimeter.
3. Estimation or actual measurement of the moisture stored in the lysimeter soil.

Lysimeter Data on Evapotranspiration Rate

In the following, our attention will be on lysimetric measurements of the evapotranspiration rate in the Eastern United States. Particularly in humid climates, lysimetry is the only practicable method and many lysimeters have been installed in the East as borne out by reviews by Kohnke, Harrold and others (5, 6, 7). Few, however, meet the requirements set forth above for adequate study of evapotranspiration. This is, in part, attributable to the fact that the lysimeters were often primarily intended for other purposes. Among recent measurements that can be considered reliable we would list:

1. The Coshocton, Ohio installation of the USDA Agricultural Research Service; work by Harrold and associates (5, 6).
2. Lysimeters at Seabrook, New Jersey of the Laboratory of Climatology; work by Thornthwaite and his group (8).
3. Lysimeters at Waynesville, North Carolina of the Tennessee Valley Authority and the North Carolina Agricultural Experiment Station; work by Gilbert (2).
4. Lysimeters at Raleigh, North Carolina of the USDA Agricultural Research Service and the North Carolina Agricultural Experiment Station; work by Van Bavel and associates (4).

These four have been selected, not implying that some others are not of equal interest. However, all four are recent installations that have been operated for several years and that meet minimum requirements.

First, attention is called to a comparison of similar covers at all four locations. At Seabrook a grass and clover mixture was studied for several consecutive years; at Coshocton a bromegrass, clover and alfalfa cover was used on all three weighing lysimeters for many years; and at Waynesville a mountain-type pasture and at Raleigh Bermudagrass were investigated for several years. The data on the evapotranspiration rates with some explanatory notes are cited in full in table 1. A direct comparison can be made by reference to figure 2. The data at Seabrook, Waynesville and Raleigh represent maximum or near-maximum values but the Coshocton data are actual values, possibly affected by moisture deficits in the profile.

Table 1—Measured evapotranspiration rate and its standard error in inches per day by months.

Month	Seabrook, N.J.*	Coshocton, O.†	Raleigh, N.C.‡	Waynesville, N.C.§
Jan.	0.032 ± 0.008	0.017 ± 0.004	-	0.019 ± 0.004
Feb.	0.022 ± 0.008	0.030 ± 0.003	-	0.029 ± 0.005
Mar.	0.042 ± 0.010	0.059 ± 0.004	-	0.049 ± 0.006
Apr.	0.087 ± 0.005	0.107 ± 0.010	-	0.101 ± 0.007
May	0.147 ± 0.008	0.165 ± 0.012	-	0.131 ± 0.009
June	0.154 ± 0.008	0.164 ± 0.007	0.168 ± 0.008	0.164 ± 0.017
July	0.190 ± 0.010	0.194 ± 0.011	0.174 ± 0.014	0.148 ± 0.008
Aug.	0.164 ± 0.008	0.133 ± 0.007	0.142 ± 0.003	0.132 ± 0.007
Sept.	0.129 ± 0.013	0.103 ± 0.007	0.116 ± 0.009	0.119 ± 0.006
Oct.	0.090 ± 0.008	0.065 ± 0.005	0.053**	0.073 ± 0.004
Nov.	0.059 ± 0.012	0.026 ± 0.003	-	0.030 ± 0.002
Dec.	0.027 ± 0.004	0.017 ± 0.004	-	0.010 ± 0.005
Annual	0.096	0.090	-	0.083

* Maximum values from grass-clover mixture, 1950-1953.
† Actual values from alfalfa-brome-clover cover, 1944-1955.
‡ Maximum values from Bermuda grass, 1956-1958.
§ Maximum values from mixed pasture, 1952-1955.
** Single value.

The Coshocton installation is a weighing lysimeter and the most accurate one. The Waynesville and Raleigh installations are percolation lysimeters, watered frequently from above. The Seabrook lysimeters are constant water table devices. In all four instances the environment was treated in the same manner as the lysimeters even though an ideal situation was not always present. Taking all these differences as well as the geographic and climatological ones into account, it is remarkable that the data are as similar as shown. We may conclude that a 10 to 20% accurate figure for maximum evapotranspiration rates from a pasture cover is well established for the geographical area covered. It seems highly desirable that similar data be procured for the Northeast, Florida, the Lower Mississippi Delta and the North Central area.

A further question worthy of attention is the variation between crops with regard to evapotranspiration rates. In making comparisons between crops it is desirable that they be compared at the same time and site. Each of the sites should meet the conditions given earlier. This rules out small plots or lysimeters adjacent to each other with different crops in each of them.

Comparisons of this nature are rare, the best available undoubtedly being made at Coshocton (6). The following figures apply to 7 years of data with corn and 14 years of data for meadow. The measurement period is 5 months for each—May through September for corn, and April through August for meadow.

Total evapotranspiration amount (May-September), corn: 21.4 inches

Total evapotranspiration amount (April-August), meadow: 22.3 inches

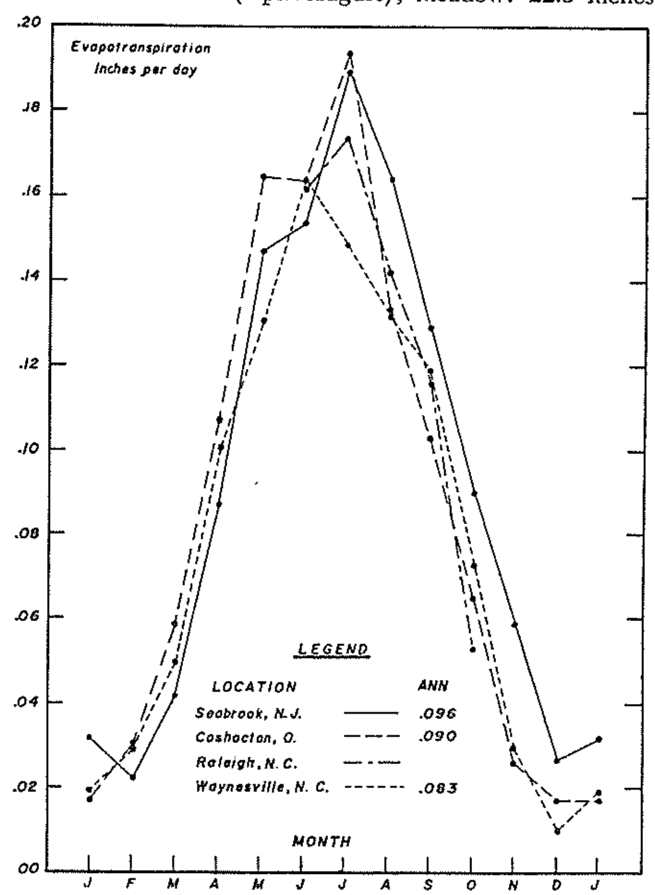

Figure 2—Measured evapotranspiration rate in inches per day on meadow covers at four locations in the Eastern United States.

Another comparison based upon monthly data and consisting of 7 values for corn and 14 values for meadow for the month of July shows:

Average daily evapotranspiration rate in July, corn: 0.21 inch

Average daily evapotranspiration rate in July, meadow: 0.17 inch

Interesting also is the comparison between wheat and meadow during May, based on 8 values for wheat and 14 values for meadow:

Average daily evapotranspiration rate in May, wheat: 0.16 inch

Average daily evapotranspiration rate in May, meadow: 0.16 inch

These comparisons were not all made in the same years and therefore are not strictly valid. However, they comprise several years and the data are accurate. They indicate minor, if any, differences between corn, wheat and meadow in evapotranspiration rates. Corn seems to give higher values during the height of its development, apparently offset by comparatively low values during its establishment.

The following, rather incomplete, comparison is based upon data from Seabrook, New Jersey:

Maximum daily evapotranspiration rate from corn, July 1948: 0.181 inch

Maximum daily evapotranspiration rate from grass, July 1950-53: 0.190 inch

At Raleigh, North Carolina, simultaneous observations on corn and Bermudagrass in 1957 and in 1958 show the following:

Maximum evapotranspiration amount from sweet corn, 100-day period, 1957: 17.2 inches

Maximum evapotranspiration amount from Bermudagrass, 100-day period, 1957: 15.8 inches

Maximum evapotranspiration amount from corn, 105-day period, 1958: 18.4 inches

Maximum evapotranspiration amount from Bermudagrass, 105-day period, 1958: 15.3 inches

The observations at Raleigh show a somewhat greater evapotranspiration from corn, a tendency which is pronounced during the tasseling and silking period.

Discussion

The data presented here tend to show that the effect of crop morphology is not large and that the evapotranspiration rate must be seen as primarily dependent upon meteorological factors when soil moisture is not limiting. However, this conclusion pertains only to such data as are available and should be regarded as preliminary. Less complete data on cotton, tobacco and some vegetables scattered throughout the literature are in line with the above statements. Alfalfa has been reported as showing values 20 to 30% higher than most other field crops. Data on forest cover are not conclusive; however, indirect data from watershed studies show generally small differences in water yield over long periods of time from various complete covers, such as forest vs. perennial pasture.

There is still a need for the procurement of monthly and annual figures on evapotranspiration rates for different crops and cropping sequences in different geographical areas for arriving at simple facts and conclusions as exemplified above. This can be done with uncomplicated percolation-type lysimeters that are properly exposed and managed. Such experiments are simple but ask more labor and attention than routine meteorological equipment, for example. A schedule of accurate observations must be maintained for several years and the lysimeter fields need constant and careful attention.

Therefore, it is mandatory to make meteorological measurements at the test sites to permit correlation of the evapotranspiration data to other, more generally available weather data. The proper choice of a meteorological variable is a question still under debate. We would choose some measurement of radiative energy, preferably of net radiation. Such measurements may range from pyrheliometers, net exchange radiometers, mechanical actinometers, Gunn-Bellani integrators, to simple sunshine recorders. There is a need for a self-powered, dependable, and low-cost radiation integrating device that does not require daily attention.

Besides gross figures on evapotranspiration rates, science and practice alike are in need of accurate daily, and even hourly, data on evapotranspiration. For example, such information is important for irrigation system design and irrigation practice (10, 11). This requires a weighing lysimeter with its attendant high cost. Up to this time, in the Eastern United States there is only one such installation at Coshocton, Ohio. It is believed that the Coshocton lysimeters have already yielded many data on short-time values of evapotranspiration but none of this information appears to have been exhaustively analyzed.

Such an effort would appear to be a first need as well as the establishment of other weighing-lysimeter systems in strategically located points. A recent Australian design (1) for a small weighing system of adequate precision deserves serious attention when major expenditure is not possible. Adequate meteorological instrumentation is definitely required with a weighing-lysimeter installation if the findings are to be generalized for maximum usefulness.

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